Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 2.76$ TeV

CMS Collaboration ; Canelli, M Florencia ; Chiochia, V ; Kilminster, B ; Robmann, P ; et al

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Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 2.76\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The double-differential inclusive jet cross section is measured as a function of jet transverse momentum p_{T} and absolute rapidity $|y|$, using proton-proton collision data collected with the CMS experiment at the LHC, at a center-of-mass energy of $\sqrt{s} = 2.76\,\mathrm{TeV}$ and corresponding to an integrated luminosity of $5.43\,\mathrm{pb}^{-1}$. Jets are reconstructed within the p_{T} range of 74 to 592 GeV and the rapidity range $|y| < 3.0$. The reconstructed jet spectrum is corrected for detector resolution. The measurements are compared to the theoretical prediction at next-to-leading-order QCD using different sets of parton distribution functions. This inclusive cross section measurement explores a new kinematic region and is consistent with QCD predictions.

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*See Appendix A for the list of collaboration members

1 Introduction

Jets are copiously produced in proton-proton (pp) collisions at the LHC. In the standard model, the hard-scattering interaction between partons inside the protons is described by perturbative quantum chromodynamics (QCD). Particle-level predictions, however, require a nonperturbative (NP) modeling of hadronization and multiple parton interactions in addition to the QCD calculation. The predicted rate and kinematics of jet production are sensitive to the composition of the proton described by the parton distribution functions (PDF) and to the strong coupling constant (α_S). The evolution of PDFs and α_S with the increase in the magnitude of the four-momentum transfer is determined by the renormalization group equations of perturbative QCD [1–3]. Precision measurements of inclusive jet production cross sections at different center-of-mass energies can be used to determine PDFs and α_S as well as to search for deviations in their behavior from QCD predictions [4]. Inclusive jet cross section measurements have been performed at the LHC [5–8] and at other high energy colliders [9–16]. The measurements (up to 592 GeV) presented here extend the jet transverse momentum reach of the previous studies.

In this study, the inclusive jet production cross section, $\sigma(\mathrm{pp} \to \mathrm{jet} + \mathrm{X})$, is measured as a function of the jet transverse momentum p_T and absolute rapidity $|y|$. The analysis is performed with data from pp collisions at $\sqrt{s} = 2.76$ TeV with the CMS experiment corresponding to an integrated luminosity of $5.43\,\mathrm{pb}^{-1}$. Originally designed as a reference for heavy ion studies, this data set also provides an opportunity to close the wide gap in jet measurements between the Tevatron at 1.96 TeV and the LHC at 7 and 8 TeV. When combined with the cross section measurements at other center of mass energies the present measurement can be used to improve PDF constraints. The data presented in this paper are collected at low instantaneous luminosity conditions with, on average, 1.2 primary interactions per triggered event. The measured cross section is compared to the prediction from a next-to-leading-order (NLO) QCD calculation, performed using the NLOJET++ (v.4.1.3) generator [17, 18] implemented in the FASTNLO (v.2.1.0) framework [19]. NP contributions to the cross section are taken into account in the theoretical prediction; electroweak contributions are negligible [20].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid which provides a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [21].

3 Jet reconstruction and event selection

The particle-flow (PF) algorithm [22, 23] is used to reconstruct and identify individual particles in an event with optimally combined information from the various subsystems of the CMS detector. The particles are identified as: charged hadrons, neutral hadrons, muons, electrons, and photons. The PF candidates are combined into jets using the anti-k_T algorithm [24] as implemented in the FASTJET software package [25]. A wide reconstruction cone with a radius of 0.7

is used to reduce the sensitivity to final-state radiation. Particles identified as charged hadrons are assigned the pion mass, while neutral hadrons are considered massless and the four-vector sum of all reconstructed particles in the jet is calculated. The measurements of jet energy and momentum in the CMS detector are affected by a number of experimental factors, such as the limited coverage of the tracking system and the nonlinear calorimeter response. The tracking system provides superior jet reconstruction (i.e., systematic uncertainties due to energy calibration and resolution) in the central region of the detector ($|\eta| < 2.4$). To correct for the detector response, the measurements are calibrated using reference processes with well-understood kinematics [26]. Jet energy corrections are derived using simulated events, generated with PYTHIA6 (v.6.4, tune Z2*) [27] and processed with GEANT4 [28]. The most recent PYTHIA6 Z2* tune is derived from the Z1 tune [29], which uses the CTEQ5L parton distribution set, whereas Z2* adopts CTEQ6L [30]. The corrections are verified in data using γ+jet and Z+jet processes, and additional corrections are applied to compensate for any mismatch between simulation and data. The correction factors depend on jet p_{T} and η, and typically range between 1.02 and 1.10, while the jet energy resolution amounts to 15% at a jet p_{T} of 10 GeV, 8% at 100 GeV, and 4% at 1 TeV.

The events are selected by a set of single-jet triggers with jet p_{T} thresholds of 40, 60, and 80 GeV with the first two triggers being prescaled. In Table 1, the effective integrated luminosity collected with each trigger and the corresponding jet p_{T} range is presented. The triggers are selected to ensure 99% efficiency for the events in the corresponding p_{T} range of the analysis.

Table 1: Effective integrated luminosities and jet p_{T} ranges for triggers used in this study.

Nominal trigger threshold (GeV)	$\mathcal{L}_{\text{int,eff}}$ (pb^{-1})	p_{T} range (GeV)
40	0.59	74–97
60	3.48	97–133
80	5.43	133–592

Events with $E_{\mathrm{T}}^{\text{miss}}/\Sigma E_{\mathrm{T}} < 0.3$ are selected, consistent with the properties of QCD multijet events, thereby removing any spurious jet-like features originating from isolated noise patterns in certain HCAL and ECAL regions. The quantities $E_{\mathrm{T}}^{\text{miss}}$ and ΣE_{T} are calculated as the negative vector sum of transverse energy and the scalar sum of transverse energy, respectively, of all PF candidates in the event. The selected events are required to have at least one well-reconstructed primary vertex. Each jet should contain more than one PF candidate. The fraction of jet energy carried by charged leptons (e, μ) should be less than 90%. In addition, jets reconstructed within the acceptance range of the tracking system ($|\eta| < 2.4$) must contain at least one charged particle. The electromagnetic energy fraction of such jets is required to be less than 99%, while the neutral-hadron and the photon energy fractions are required to be less than 90%. The jet selection efficiency is estimated to be 99% or higher for all p_{T} and rapidity ranges used in this study.

4 Cross section measurement

The double-differential jet cross section is calculated as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{1}{\epsilon\mathcal{L}_{\text{int,eff}}} \frac{N}{\Delta p_{\mathrm{T}}\ (2\,\Delta|y|)}, \tag{1}$$

where $\mathcal{L}_{\text{int,eff}}$ is the effective integrated luminosity corrected for trigger prescales, ϵ is the overall reconstruction efficiency including the trigger and jet selection efficiencies, Δp_{T} and $\Delta|y|$ are the sizes of a particular jet p_T and rapidity bin, and N is the number of jets in that bin. Six uniform bins in $|y|$ are used between 0.0 and 3.0. The jet p_T values range from 74 to 592 GeV, with bin sizes increasing in proportion to the p_T resolution.

In order to facilitate the comparison of measurements with theoretical predictions, the jet p_T spectrum is corrected for detector effects. Since the p_T spectrum is steeply falling, the number of jets migrating out of a bin into the higher adjacent bin significantly exceeds the number of jets migrating to the lower adjacent bin. The unfolding procedure compensates for this effect and recovers the particle-level spectrum from the observed spectrum. The detector response function is determined using multijet events simulated with the PYTHIA6 (v.6.4, tune Z2) [27, 31] event generator. A detailed detector simulation is carried out using the GEANT4 software to model the particle interactions in the detector material.

The detector is characterized by a response function that represents the probability density to reconstruct a jet with transverse momentum p_T^{det} when the particle-level jet transverse momentum is p_T^{part}. The response function is initially derived by calculating jet resolution in Monte Carlo (MC) simulation for every p_T and $|y|$ bin. Jet resolution in data is found to be worse than in simulations [26]. The response function is corrected for this defect by degrading the resolution by factors $c^{data/MC}$ that vary with $|y|$ as listed in Table 2.

Table 2: The factors used to scale jet resolution determined in simulations to match the resolution observed in data.

$\|y\|$	$c^{data/MC}$
0.0–0.5	1.079 ± 0.026
0.5–1.0	1.099 ± 0.028
1.0–1.5	1.121 ± 0.029
1.5–2.0	1.208 ± 0.046
2.0–2.5	1.254 ± 0.062
2.5–3.0	1.395 ± 0.063

The response matrix is constructed by convolving the response function with the p_T^{part} spectrum predicted by NLO QCD calculations and the CT10 PDF set [32]. (Results with other PDF sets are discussed in Sec. 6.) The response function is represented by a kernel density estimation (KDE) technique that accurately models the tails of the distribution. The theoretical p_T^{part} spectrum is fitted with an exponential of a continuously differentiable function (Akima spline) [33]. This spline function is sampled many times and convolved with the KDE response function to obtain the response matrix. The D'Agostini iterative unfolding method [34] is used, as implemented in the ROOUNFOLD software package [35]. The unfolding procedure is regularized by early termination of iterations; four iterations are performed in each rapidity bin.

5 Theoretical predictions

The theoretical predictions are derived at NLO using QCD calculations with NLOJET++ [17, 18], and corrected for the NP contributions from hadronization and multiple parton interactions. Electroweak corrections are negligible at 2.76 TeV according to the studies performed in Ref. [20]. The factorization and renormalization scales are set to the jet p_T ($\mu_F = \mu_R = p_T$). The theoretical predictions of the inclusive jet cross section are derived using five recent PDF sets at NLO, as listed in Table 3, with the central values of $\alpha_S(M_Z)$ for each PDF set. Most are determined in a variable-flavor number scheme, except for the ABM11 PDF set, which employs a fixed-flavor number scheme with the number of active flavors (N_f) set to 5 or 6. The details related to determination of the PDFs are described in the corresponding references.

Table 3: The PDF sets used for deriving cross section predictions are given with the number of active flavors (N_f), the values and ranges of $\alpha_S(M_Z)$ used for the fits, and corresponding references.

Base set	N_f	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ range	Reference
CT10	≤ 5	0.118	0.112–0.127	[32]
MMHT14	≤ 5	0.120	0.108–0.128	[36]
NNPDF3.0	≤ 6	0.118	0.115–0.121	[37]
HERAPDF1.5	≤ 5	0.1176	0.114–0.122	[38]
ABM11	5	0.118	0.110–0.130	[39]

The NP effects include hadronization of parton cascades leading to the formation of color neutral jets and multiple interactions of spectator partons within the colliding protons that can result in the appearance of additional jets. The corrections are derived using two event generators with different models for parton cascades and hadronization: PYTHIA6 (v.6.4, tune Z2) [27, 31] and HERWIG++ (v.2.5.0, tune UE_EE_3C) [40, 41]. In PYTHIA6, the hadronization is simulated with the Lund string fragmentation model [42] while HERWIG++ employs the cluster fragmentation model [43]. The p_T- and $|y|$-dependent correction factors for the NP effects, C_{NP}, are derived from simulation as a ratio of differential jet cross sections with hadronization and multiple parton interactions turned on and off. The final correction factors are obtained by averaging PYTHIA6 and HERWIG++ predictions. The theoretical cross section is then calculated as $\sigma_{theory} = \sigma_{NLO}\, C_{NP}$. The C_{NP} factors vary between 1.02 and 1.10 in the p_T and rapidity range of this analysis.

6 Systematic uncertainties

The major experimental uncertainties in this analysis come from imperfect measurement of jet energy, limited precision in simulating jet energy resolution, and imprecise knowledge of integrated luminosity. The first source affects the jet spectrum observed in data, while the second modifies the detector response matrix used in the unfolding procedure. The third source, measured integrated luminosity, contributes an overall cross section uncertainty of 3.7% [44]. The uncertainty associated with the jet energy determination consists of several independent contributions identified in the process of deriving the jet energy corrections. These contributions are described in detail in Ref. [26]. The corresponding cross section uncertainty is 5–22% for the low-rapidity bins ($|y| < 2.5$), increasing to 78% in the highest rapidity bin ($2.5 \leq |y| < 3.0$). The jet energy resolution uncertainty is estimated using the uncertainties in the $c^{data/MC}$ scaling factors presented in Table 2. For the rapidity region $|y| < 2.5$, the corresponding cross section uncertainty is 2–3%, increasing to 22% for the most forward rapidity bin. The higher uncertainty at forward rapidities is caused by the significant increase in the jet energy and resolution uncertainties, and the more steeply falling p_T spectrum in comparison with the central rapidity region.

The energy offset due to additional interactions in the same bunch crossing (pileup) is small. For the lowest p_T jets considered (74 GeV) the pileup contributes an average of only 0.3% of the energy. This fraction decreases with increasing p_T. Consequently, pileup corrections are not required and the associated uncertainties are negligible. An uncertainty arising from the potential mismodeling of trigger and jet selection requirements is found to be 1%. The unfolding uncertainty due to the initial theoretical model is calculated by testing various models and finding the effect is negligible. The sum in quadrature of all experimental systematic uncertainties in the cross section is, on average, 6% at low rapidities ($|y| < 2.0$) and varies from 10% to 80% at higher rapidities ($2.0 \leq |y| < 3.0$), across the corresponding p_{T} ranges.

The uncertainty in the theoretical cross section prediction is estimated from the PDF uncertainties, the choice for the factorization and renormalization scales (μ_{F} and μ_{R}), and the variation in the modeling of NP corrections. The PDF uncertainty, for all PDF sets except NNPDF3.0, is calculated as the change in the cross section caused by varying decorrelated PDF parameters. The relevant PDF eigenvectors are provided in the PDF sets along with the central values. The uncertainty due to each parameter is determined at 68% confidence level (CL), and the resulting asymmetric uncertainties are combined in quadrature. In the case of NNPDF3.0, the PDF set contains an ensemble of replicas corresponding to one standard deviation in the PDF. The PDF uncertainty is calculated by evaluating the standard deviation in the cross section derived by using different replicas. The uncertainty due to the variation of the value of $\alpha_{\mathrm{S}}(M_{\mathrm{Z}})$ in the PDF sets is found to be much smaller than other uncertainties (<1%) and is not included. The scale uncertainty is determined by varying the factorization and renormalization scales with respect to the nominal value ($\mu = \text{jet } p_{\mathrm{T}}$) using the following combinations of ($\mu_{\mathrm{F}}/\mu,\ \mu_{\mathrm{R}}/\mu$) ratios: (0.5, 0.5), (1, 0.5), (0.5, 1), (1, 2), (2, 1), and (2, 2). The largest deviation from the nominal cross section, found separately in each p_{T} and $|y|$ bin, is taken to represent the scale uncertainty. The scale uncertainty is asymmetric and its distribution is skewed towards lower cross sections. The largest deviation from the average value of the C_{NP} correction factors, which are obtained with the PYTHIA6 and HERWIG++ generators as discussed in Section 5, is used as the measure of the NP modeling uncertainty. It contributes a 2–5.6% uncertainty in the cross section prediction. The uncertainties in the theoretical predictions differ for each PDF set considered, and typically vary in the 10–20% range over most of the kinematic region.

7 Results

The measured inclusive jet cross section and the theoretical predictions are compared in Figs. 1–3. In Fig. 1, the double-differential cross section is plotted as a function of jet p_{T} and $|y|$. The theoretical prediction obtained with the CT10 PDF set is shown as well. A more detailed comparison for all $|y|$ bins is presented in Fig. 2, where the ratios of data to theory using the CT10 PDF set are shown. Within the uncertainties, the data are well described by NLO QCD in the full kinematic range explored. In Fig. 3, the data, with NP corrections, are compared in a similar manner to the predictions from other PDF sets, normalized to the CT10 prediction. In general, all predictions describe the data well. Within experimental and theoretical (not shown) uncertainties, only the comparison to the prediction from the ABM11 PDF set exhibits slight differences between the data and theory, an effect that has been observed also in other measurements, e.g. Ref. [4].

8 Summary

A measurement of the double-differential inclusive jet cross section was presented. The data were collected by the CMS detector in pp collisions at $\sqrt{s} = 2.76\,\mathrm{TeV}$, with an integrated luminosity of $5.43\,\mathrm{pb}^{-1}$. The measurement covers the jet kinematic ranges of $74 \leq p_{\mathrm{T}} < 592\,\mathrm{GeV}$ and $|y| < 3.0$.

A detailed study of the experimental and theoretical uncertainties has been performed. Contributions to the experimental systematic uncertainty were evaluated from the jet energy corrections, jet energy resolution, and integrated luminosity. Jet energy corrections dominate the

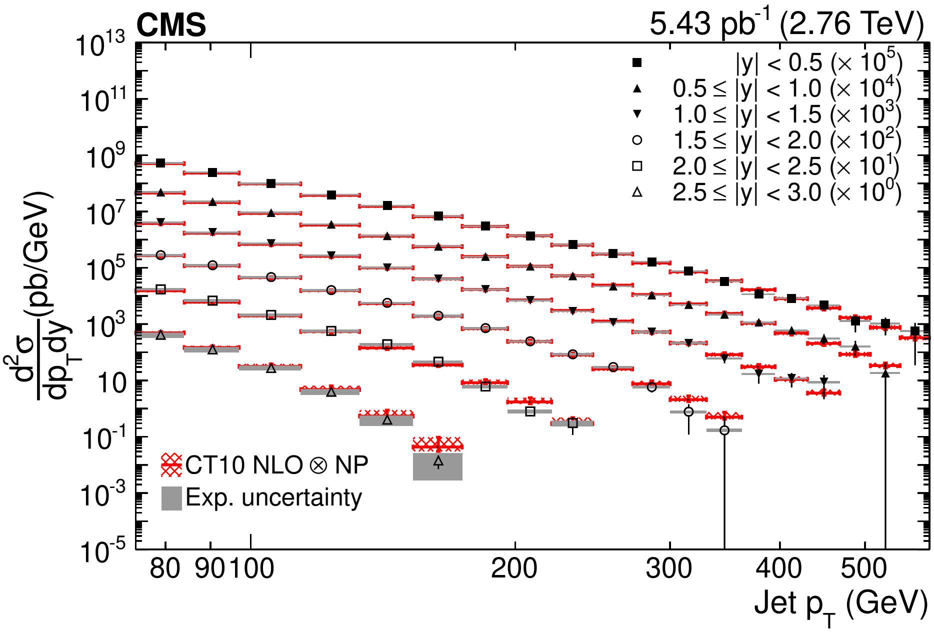

Figure 1: The inclusive jet production cross section, measured at $\sqrt{s} = 2.76\,\text{TeV}$, shown as a function of jet p_T in six $|y|$ bins, as indicated by different symbols. The statistical (systematic) experimental uncertainties are indicated by vertical error bars (filled bands). The measurements are compared to the NLO QCD prediction using CT10 PDF set. The theoretical uncertainties are represented by hatched bands.

experimental uncertainty, followed by smaller contributions from jet energy resolution and luminosity. The theoretical uncertainty is dominated by the missing higher-order corrections that were estimated by varying the renormalization and factorization scales, and the PDF uncertainty; the contribution of nonperturbative correction uncertainty is small.

The data are corrected for detector resolution and efficiencies. The measured cross sections are compared to NLO QCD predictions obtained using different PDF sets. These cross section measurements test and confirm the predictions of QCD at $\sqrt{s} = 2.76\,\text{TeV}$ and extend the kinematic range compared to previous studies.

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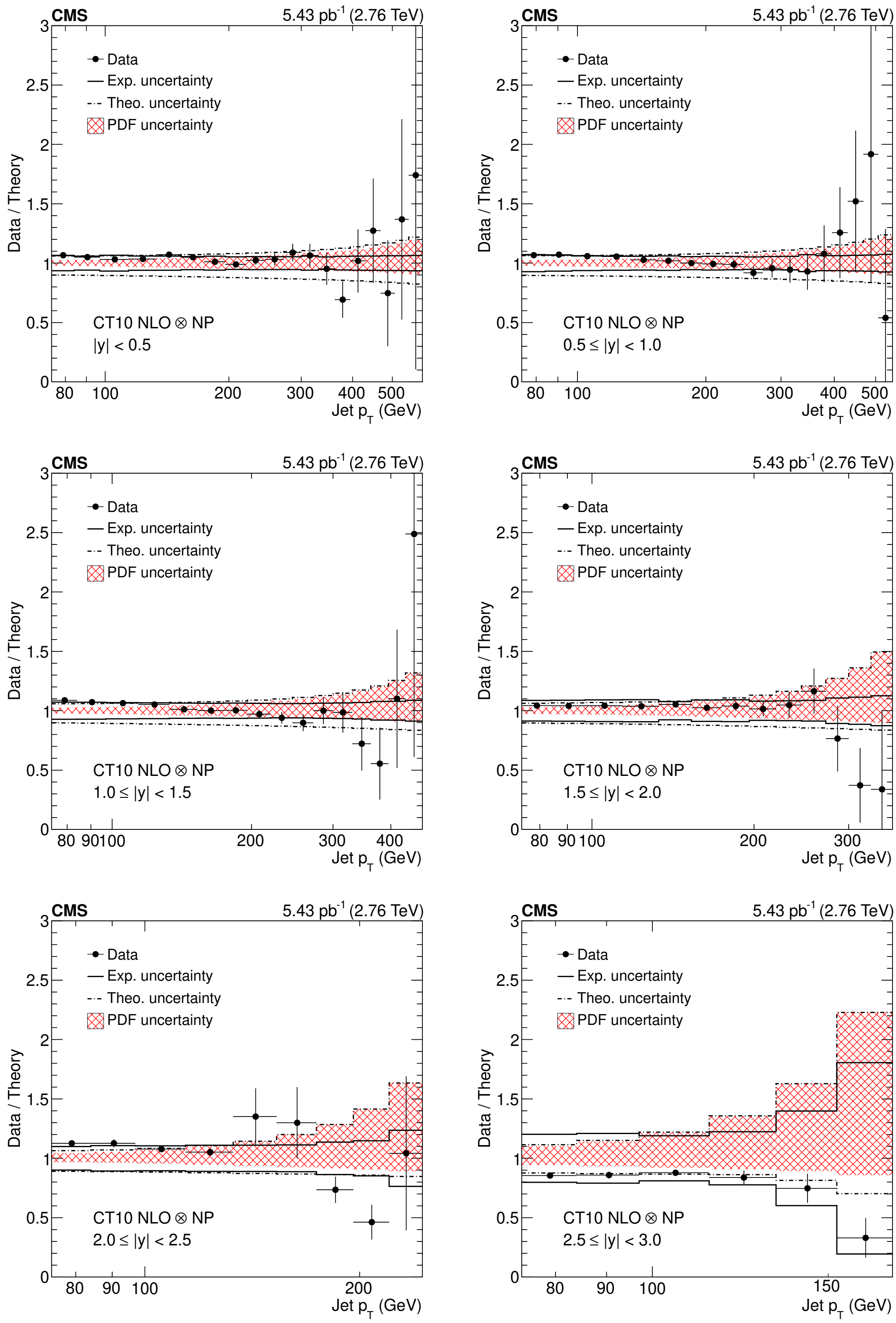

Figure 2: The ratio of the measured inclusive jet production cross section (closed symbols) at $\sqrt{s} = 2.76\,\text{TeV}$ to the theoretical prediction using the CT10 PDF set is shown as a function of jet p_{T} in each measured $|y|$ range with the statistical (vertical error bars) and systematic (solid lines) experimental uncertainties. The total theoretical uncertainties are shown by the dash-dotted lines with the contribution from PDF uncertainties (hatched band).

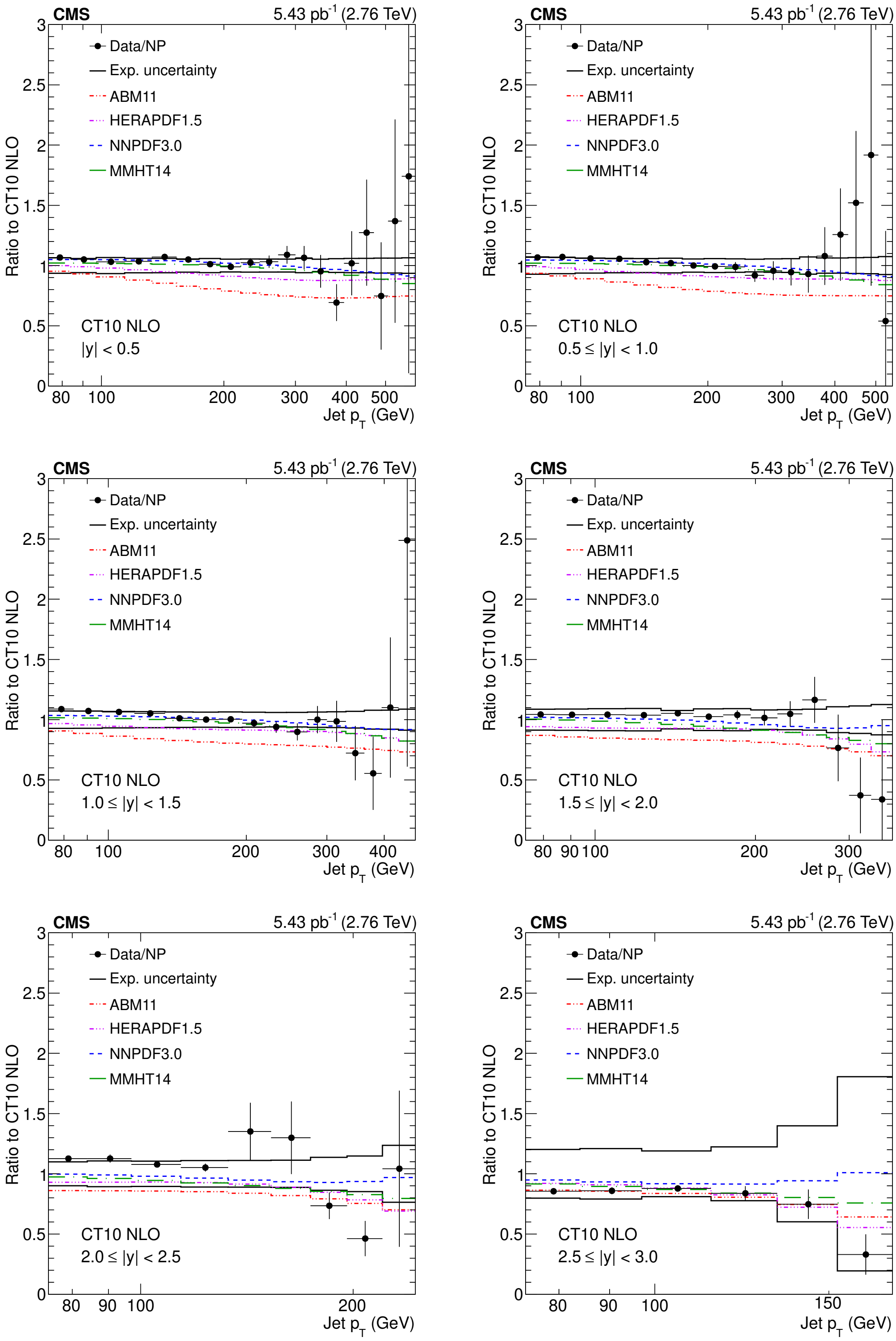

Figure 3: The same data shown in Fig. 2 are presented showing comparisons to the NLO QCD predictions using a variety of PDFs, which are denoted by different line styles. The uncertainties corresponding to the QCD predictions are not shown. For simplicity, the NP corrections needed for the various QCD predictions have been applied to the data in this figure.

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